The Square Kilometre Array: A path to unveil the unknown

Our exploration of the cosmos has answered many questions – but in the process, even more fundamental questions have arisen. Sergio Colafrancesco looks at how the SKA will help to answer these questions.

There are some fundamental questions that still need to be answered before we can say that we fully understand the Universe: What is the nature of the Dark Side of the Universe? What is the origin of the most extreme events in the Universe? What is the nature of the highest energy particles in the Universe? What is the origin of the cosmic magnetic fields that confine these particles?

These are the questions that scientists are being asked to address by the major science and technology funding agencies around the world – they are serious questions for humankind. But before attempting to answer, we could (or should) ask: why are we asking these questions?

Our exploration of the cosmos has provided many answers about the evolution of our Universe and its structures – stars, galaxies and very large clusters of galaxies. But this understanding has forced us to ask even more fundamental questions about the nature of matter, the nature of fields and the nature of the particles that are contained in the Universe.

The nature of matter

The detailed observations of the cosmic microwave background anisotropies from the Planck space experiment have shown that we live in a Universe whose matter and energy composition is made up of:

- 4.9% normal matter – the standard particles and atoms and the known radiation that make up the world as we know it
- 26.8% dark matter – an unknown form of matter known only for its gravitational effect
- the remaining 68.3% is made up of dark energy – an unknown form of possible energy that is theorised to produce the accelerating rate of expansion of the Universe.

We also know that all particles in the Universe must have a mass and recently a fundamental particle, probably the Higgs boson, was finally discovered at the Large Hadron Collider (LHC) at CERN near Geneva, Switzerland. This provides the answer to the nature of the visible part of our Universe – the 4.9% of total cosmic matter determined cosmologically by the Planck experiment.

These are great successes in the history of science but leave us with other more fundamental questions, some of which are outlined at the beginning of this article. Answering these questions requires more large and sensitive experiments to provide definitive answers. The square kilometre array (SKA) is one of the ‘big science’ projects that will be used over the next few decades to help us to answer some of the most important questions on the nature of the ‘unknown’ in our Universe. Let’s see how.

SKA and the nature of the dark side of the Universe

We have known about dark matter (DM) for 80 years – since 1933 when Fritz Zwicky proposed that it was...
‘dark matter’ that made up the ‘missing mass’ budget necessary to explain his observations of the Coma galaxy cluster. When he calculated the gravitational mass of the galaxies within this cluster, he obtained a value at least 400 times greater than expected from their luminosity, which meant that most of the matter must be dark. Modern calculations get a smaller factor of difference, but still infer that most of the matter must be dark.

Scientists are eagerly trying to detect DM particles in deep underground experiments by measuring the energy deposited by the DM particle when it hits normal atoms in a pure laboratory environment. However, no definite signal has been detected to date. However, cosmologists are able to look at the radio emission produced by the decay of hypothetical particles called neutralinos into elementary particles that decay further into electrons and positrons. This will provide detailed information on the nature of the fundamental DM particles that can be recorded by the SKA. The SKA will be able to record very weak radio signals, so this will probably be the only experimental set-up that could detect DM radio emission and so shed light on the elusive nature of DM – which is so fundamental to the existence of the Universe and its structures.

The Higgs boson

The Higgs boson or the Higgs particle is an elementary particle that was originally theorised in 1964. It was tentatively ‘confirmed’ on 14 March 2013. It is named after the physicist Peter Higgs, who was one of several physicists who proposed that the particle must exist.

In particle physics, the existence of the Higgs boson is necessary to explain why some fundamental particles have mass when the symmetries that control the ways in which they interact should mean that they have no mass. In particle physics, symmetry is a physical or mathematical feature of the system that is preserved under some change.

The existence of such a particle was so important to understanding the physics that underlies our world and the Universe that we are part of, that scientists have spent 40 years searching for the particle. The LHC was built specifically to search for it – and in the course of this search has also helped to answer many more questions about the nature of matter.

The SKA and the origin of magnetic fields in the Universe

To generate radio emissions that we observe by using radio telescopes such as the SKA and MeerKAT, cosmic structures need high-energy particles (like electrons and positrons travelling at almost the speed of light). But there must also be a ‘field’ that these particles can interact within to produce the radio synchrotron emission. This is the magnetic field that every particle in the Universe experiences – we also experience this daily. However, nobody knows how this magnetic field is produced in the environments of galaxies. Therefore this observation brings us to another fundamental question: what is the origin of magnetic fields in the Universe?

We know that stars, planets, galaxies and even diffuse interstellar gas are magnetised. This cosmic magnetism cannot be attributed to permanent magnets like the ones which come in a science kit, but to the motion of huge clouds of plasma which are electrically charged, which move within the cosmic structures we observe.

The challenge in studying cosmic magnetism is that while stars and galaxies can be seen directly by the light they emit, magnetic fields are invisible to even the largest telescopes. Astronomers thus need to employ a variety of indirect methods to study magnetism. For example, we know that synchrotron emission is produced when fast-moving electrons are trapped in magnetic fields, like planets caught by the Sun’s gravity.
If we see a body in the Universe that is emitting synchrotron emission, we know that this object must be magnetic, and we can use its properties to determine how strong its magnetism is and what direction a compass might point if we were near it.

One problem with this approach is that many magnetic objects in space are not energetic enough to produce detectable synchrotron emission. But we can study their magnetism using a remarkable effect known as ‘Faraday rotation’. In this effect polarised light from a background radio source is changed when it passes through objects in which significant magnetism is present. The change is subtle, involving the angle at which the vibrating light waves are inclined, but can be measured with radio telescopes, and can be used to calculate the strength of the magnetic field in the foreground object.

Studying cosmic magnetism in this way is relatively easy. However, it is often difficult to apply this technique, because only rarely does a random galaxy or gas cloud happen to lie in line with a bright background object, so that we can detect the consequent Faraday rotation and thus measure its magnetic properties. But because the SKA will be so much more sensitive than current radio telescopes, we can use it to revolutionise the study of magnetic fields in space. If we point the SKA at any part of the sky, we will detect radio emissions from thousands of faint, distant galaxies, spread like grains of sand all over the sky. These galaxies will be spaced so closely together that we can use the Faraday rotation of their polarised radio emissions to make detailed studies of the magnetism from all sorts of foreground objects.

Even if we want to study a relatively small cloud of gas, there will be hundreds of background galaxies whose light shines through it, allowing us to build up a detailed picture of the cloud’s magnetism.

This new technique will allow us to address many important unanswered questions. What is the shape and strength of the magnetic field in our Milky Way, and how does this compare to the magnetism in other galaxies? Is the overall Universe magnetic? If so, has the Universe’s magnetism affected the way in which individual stars and galaxies form? And ultimately, where has all this magnetism come from?

These are all questions we can hope to address with the unique and fascinating capabilities of the SKA. We know that there are magnets everywhere in space. But with the SKA, we will understand what these magnets look like, and where they came from.

The technology underpinning the SKA has then the potential to unveil the nature of the DM particles we have already discussed by detecting the radio emission produced by DM particle annihilation in galaxies and galaxy clusters.

The SKA and the origin of cosmic rays
Magnetic fields inside galaxies and clusters of galaxies also have a property that allows them to confine plasma and high-energy particles – called cosmic rays. And intergalactic space is able to guide the highest-energy cosmic rays as they pass through space to reach our planet. We observe these very-high-energy cosmic rays carrying the highest energies in the Universe, up to $10^{20}$ eV. This brings us to answer the next question: *what is the origin of cosmic rays?*

The protons that constantly smack into Earth’s atmosphere at near the speed of light get their huge energies from exploding stars – supernovae. – or from powerful jets coming out of black holes in the centre of active galaxies – active galactic nuclei. We have long suspected this, but direct evidence for the idea has been difficult to come by – until now.

Cosmic rays are any charged particles arriving at Earth from space. Nearly all of them are protons, and some have been accelerated to speeds higher than any achieved by a particle.
accelerator on Earth. Although we have known about cosmic rays since 1912, their origins have remained a '100-year-old mystery'.

Possible sources of cosmic rays are the violent outburst of a supernova within our Galaxy, the Milky Way. The material blown out in the process moves so quickly that it creates a shock wave. Whenever a proton crosses the shock wave boundary, it gets a powerful kick.

Because protons are charged, they can get caught in magnetic fields which carry them back and forth across the shock many times, like a tennis ball bouncing back and forth across a net. Eventually their energy gets great enough that they can leave the shock region. This is a newborn cosmic ray.

Cosmic rays diffusing in the magnetised shock region produce radio emissions that can be detected with our radio telescopes. The SKA will be able to discover the sites of acceleration of these cosmic rays in every corner of our Galaxy, as well as in many thousands of external galaxies, thus proving the universal origin of cosmic rays and of the accelerating regions.

But magnetic fields can also deflect cosmic rays on their way to our detectors. By the time they reach Earth, their directions are totally scrambled, making it hard to determine their origin.

Thus, another approach to the problem is needed – and gamma rays provide it. We know that when the high-energy protons collide with low-energy protons further out, the violence of the collision indirectly creates gamma rays. These do not carry a charge and so travel in straight lines, unaffected by magnetic fields.

Because of the law of conservation of energy, the gamma rays produced during the proton collisions will have a minimum energy of around 150 - 200 megaelectronvolts each. If lots of protons are colliding near the supernova remnant, there should be more gamma rays with that energy or higher coming from that region – and almost none with lower energies. That's exactly what we are starting to see with gamma-ray telescopes such as Fermi and HESS. This is a characteristic feature that absolutely and uniquely tells us that what we are seeing are gamma rays from accelerated protons. The combination of the SKA and its high-energy relative, the Cherenkov telescope array (CTA), will tell us the complete story of the acceleration mechanism and the position of the most efficient acceleration sites in the Universe.

**The Cherenkov Telescope Array (CTA)**

This will consist of two arrays of telescopes in the two hemispheres, allowing full coverage of the sky. The telescopes will be ground-based very-high-energy gamma-ray telescopes. The southern CTA will cover about 10 km² of land with around 100 telescopes that will monitor all the gamma-ray energy ranges towards the centre of the Milky Way and the galactic plane. The northern CTA will cover 1 km² and be composed of 30 telescopes. These telescopes will be targeted at extragalactic astronomy.

This doesn't explain the origin of all cosmic rays, however. Some of them are particles called muons or positrons instead of protons – and one specific class, the ultra-high-energy cosmic rays (UHECRs), require much more extreme acceleration mechanisms and are most probably produced from outside our Galaxy. This brings us to the last question we ask here: what is the origin of the extreme accelerators in the Universe?

Cosmic rays are energetic particles from deep in outer space – mainly protons, the bare nuclei of hydrogen atoms, plus some heavier atomic nuclei. They most probably acquire their energy when naturally accelerated by exploding stars. A few rare cosmic rays pack an astonishing wallop, however, with energies massively greater than the highest energy ever attained by human-made accelerators like CERN's Large Hadron Collider. Their sources are a mystery.

Nature is capable of accelerating elementary particles to macroscopic energies. There are basically only ≈
two ideas on how this happens: i) in gravitationally driven particle flows near the supermassive black holes at the centres of active galaxies, and ii) in the collapse of stars to a black hole, seen by astronomers as gamma ray bursts (GRBs). In active galactic nuclei (AGNs) the black holes suck in matter and eject enormous particle magnetic jets, perpendicular to the galactic disk, which could act as strong linear accelerators. As for GRBs, some are thought to be the result of the collapse of supermassive stars – hypernovae – while others are thought to be collisions of black holes with other black holes or neutron stars. Both sources are extragalactic and both require the existence of very powerful jets of plasma ejected at speed similar to the speed of light. It is possible that the UHECRs are accelerated in the immediate vicinity of the very massive and compact central object (say the BH) and then they acquire extremely high energy that allows them to escape the acceleration region, travel through the intergalactic magnetic field and reach the top of the Earth's atmosphere, where they produce a shower of lower-energy particles and associated emissions that can be detected with our telescopes.

The SKA will be able to shed light on the nature of the jets in external AGNs, and especially the nearby radio galaxies like Centaurus A, by observing, with extreme spatial resolution and sensitivity, the structure of the jet and their radio (polarised) emissions that will tell us (in combination with the CTA observations at the opposite end of the electromagnetic spectrum) both the location and the nature of the extreme accelerators in the Universe. But the SKA will also be able to observe the radio emissions generated in the atmosphere of the Earth by the particles produced in the shower initiated by the UHECR accelerated far in the Universe, thus reconstructing the whole picture (together with the complementary observations from CTA) of the extreme events in our Universe.

**Epilogue**

We have already discovered much about the origin and evolution of the Universe and we have reasonable confidence in describing its basic laws. However, we are now faced with more fundamental questions. To answer these questions we need to maintain the humility of science and listen to the whispers of the Universe.

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**Suggested reading**

Planck experiment: [http://www.esa.int/Our_Activities/Space_Science/Planck](http://www.esa.int/Our_Activities/Space_Science/Planck)

LHC at CERN: [http://home.web.cern.ch/about/accelerators/large-hadron-collider](http://home.web.cern.ch/about/accelerators/large-hadron-collider)

Newton I. Philosophiæ Naturalis Principia Mathematica (the Principia), first published on 5 July 1687.

Fermi E. 1949: Phys. Rev. 75:1169